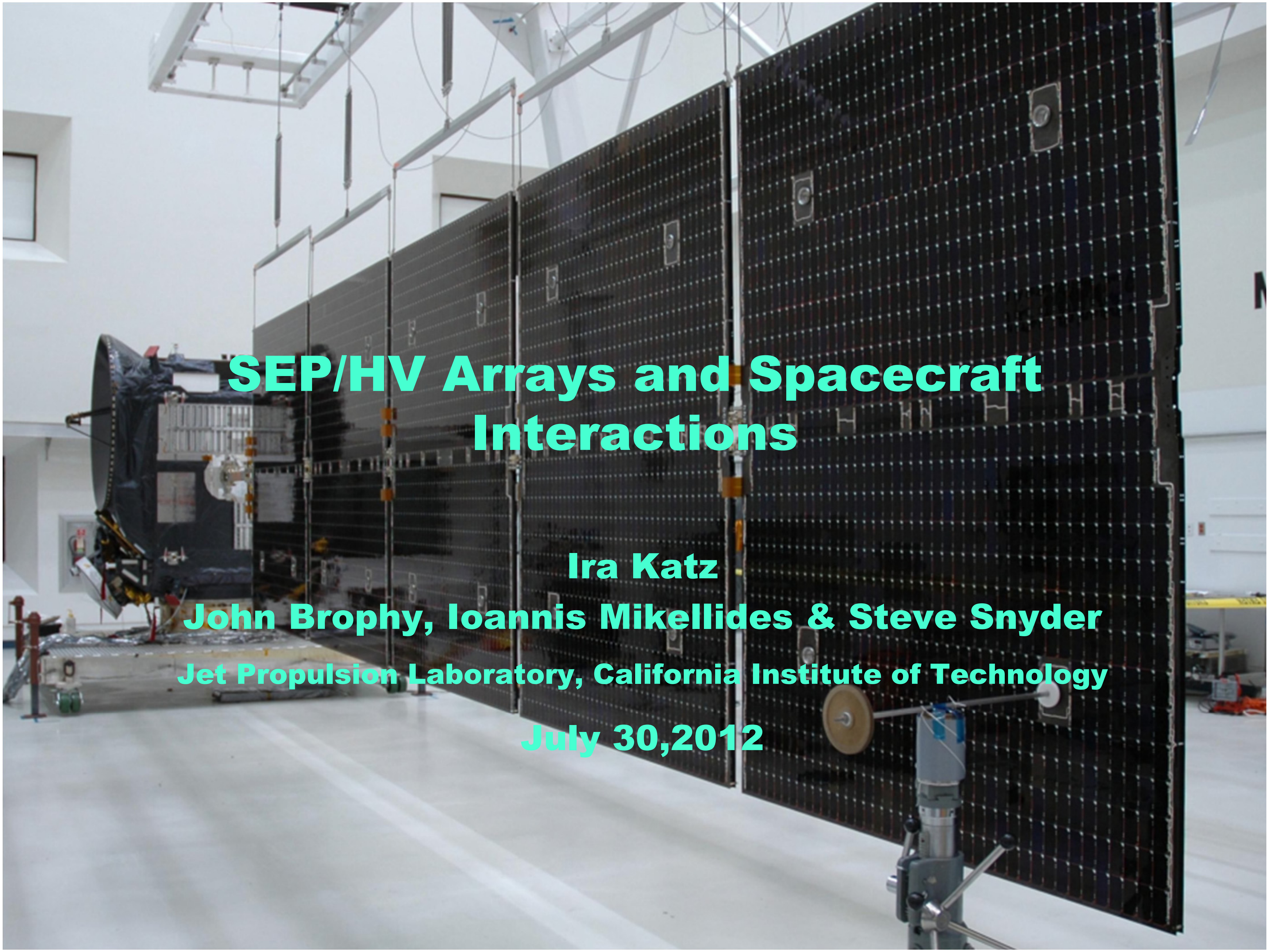


SEP/HV Arrays and Spacecraft Interactions

Ira Katz

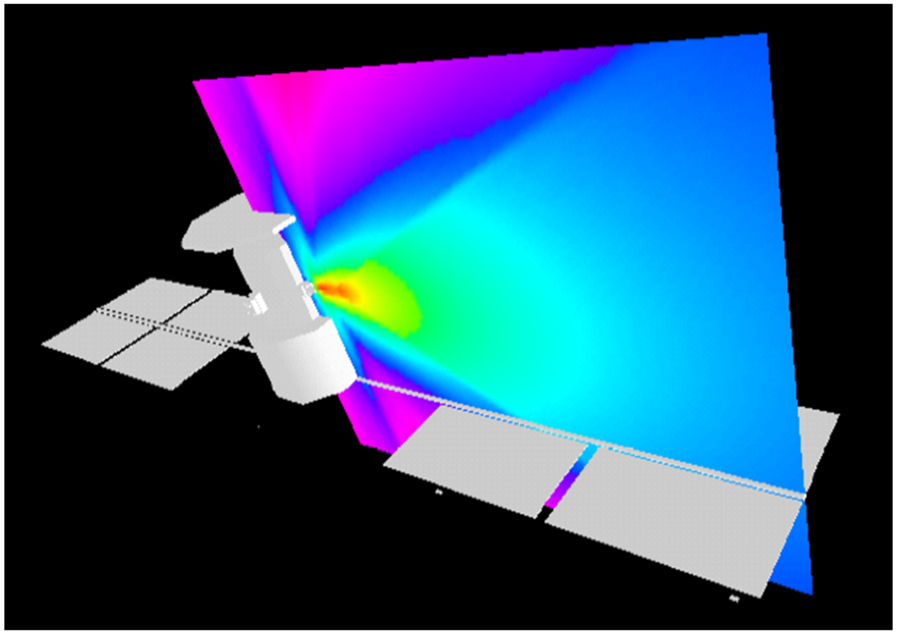
John Brophy, Ioannis Mikellides & Steve Snyder

Jet Propulsion Laboratory, California Institute of Technology

July 30,2012

Solar Electric Propulsion (SEP) High Voltage Arrays and Spacecraft Interactions

- Solar Arrays operate in plasma – not in a vacuum
- High Voltage Solar Array – Plasma Interactions have been studied for decades
  - Cells at negative potentials arc
  - Cells at positive potentials collect current
- High Voltage solar array arcing has caused on-orbit failures
  - Reproduced in the lab
  - Preventative measures have been implemented
- Electric Thruster Plume interactions
  - Conventional : Electrically Isolated Power Processing Unit (PPU)
  - Advanced Technology: Direct Drive



Electric Prolusion Interaction Code (EPIC) calculation of the Hall thruster plume plasma environment on the Express-A spacecraft

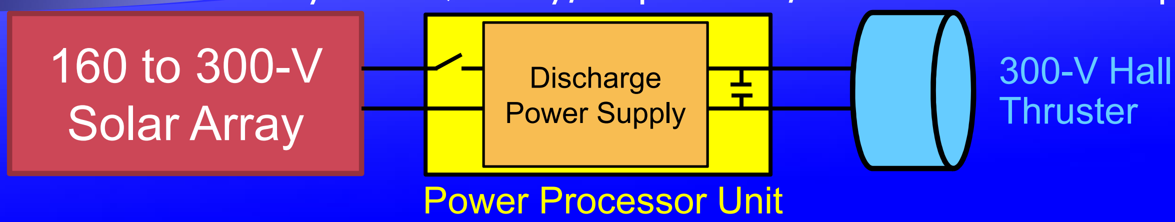
From "ASSESSMENT OF SPACECRAFT SYSTEMS INTEGRATION USING THE ELECTRIC PROPULSION INTERACTIONS CODE (EPIC)" Ioannis G. Mikellides*, Robert A. Kuharski†, Myron J. Mandell‡, Barbara M. Gardner, **AIAA 2002-3667**

If you understand how plasma interacts with solar arrays, operating at the voltages needed for Hall thruster Direct Drive isn't that difficult.

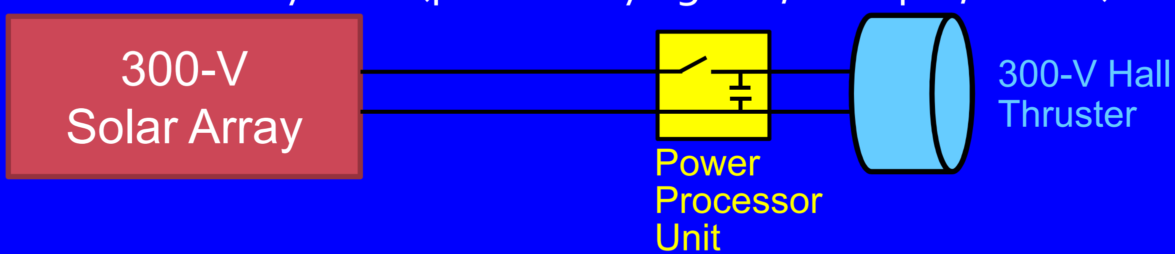
Direct-Drive

Matches a 300-V solar array with a 300-V Hall thruster

Conventional System (heavy, expensive, difficult to develop)

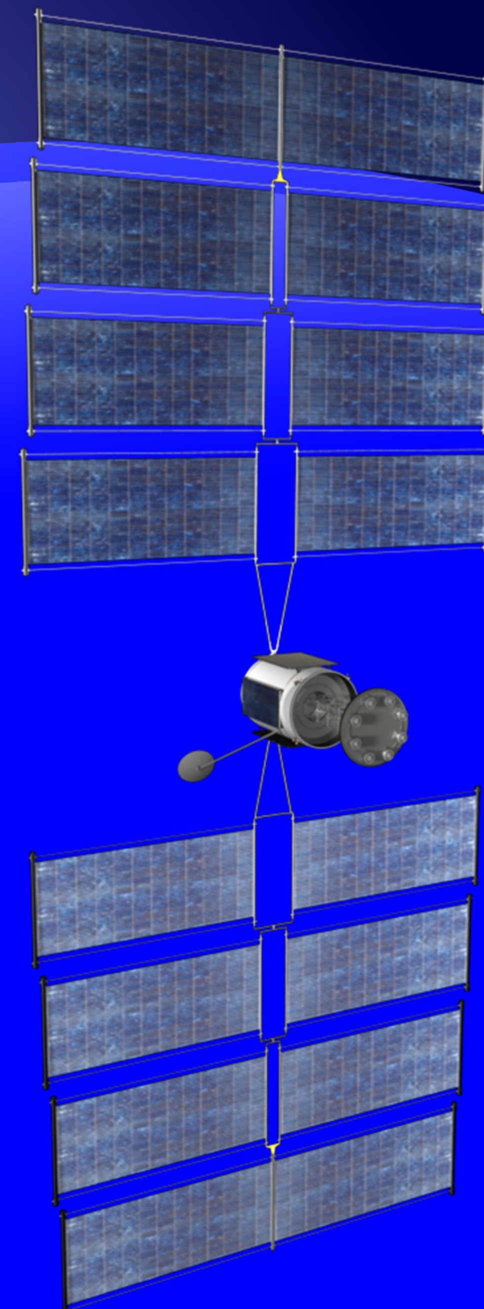


Direct-Drive System (potentially lighter, cheaper, easier)



Direct-Drive:

- Improves the power system efficiency from ~92% to ~99%
- Reduces the PPU mass by 70%
- Reduces the radiator mass by 80%
- Reduces the solar array mass, propellant mass, tankage mass, and structure mass



300-kW SEP Vehicle for Crew Transport in Deep Space

SEP Direct Drive Concept Originated at NASA/GRC (nee NASA/Lewis Research Center) in the 1970's

- Direct Drive for Ion Thrusters

Herron, B.G., and P.W. Opjordan, "High Voltage Solar Arrays with Integral Power Conditioning," AIAA 70-1158, AIAA 8th Electric Propulsion Conference, Stanford, CA, Aug. 31- Sep. 2, 1970.

West, J.L., "Ion Drive Technology Readiness for the 1985 Halley Comet Rendezvous Mission," AIAA 78-641, AIAA/DGLR 13th International Electric Propulsion Conference, 1978.

Atkins, K. and C. Terwilliger, "Ion Drive: A Step Toward 'Star Trek'," AIAA 76-1069, Key Biscayne, FL, Nov. 15-17, 1976.

Gooder, S.T., "Operational Compatibility of 30-centimeter-diameter Ion Thruster with Integrally Regulated Solar Array Power Source," NASA TN D-8428, July 1977.

Parks, D.E. and Katz, I., "Spacecraft-Generated Plasma Interaction with High Voltage Solar Array," AIAA 78-673, AIAA/DGLR 13th International Electric Propulsion Conference, 1978.

- Direct Drive for Hall Thrusters

Hamley, J.A., Sankovic, J.M., Miller, J.R., O'Neill, M.J., Lynn, P., and S. R. Olseson, "Hall Thruster Direct Drive Demonstration," AIAA 1997-2787, 33rd Joint Propulsion Conference, Seattle, WA, July 6-9, 1997.

Jongeward, G.A., Katz, I., Mikellides, I.G., Carruth, M.R., King, D.Q., Ralph, E.L., and Peterson, T., "High Voltage Solar Arrays for a Direct Drive Hall Effect Propulsion System, IEPC-01-327, 27th International Electric Propulsion Conference, Pasadena, CA, Oct. 15-19, 2001.

Mikellides, I.G., Jongeward, G.A., Schneider, T., Peterson, T., Kerslake, T.W., and D. Snyder, "Solar Arrays for Direct-Drive Electric Propulsion: Electron Collection at High Voltages," *J. of Spacecraft and Rockets*, Vol. 42, No. 3, May-June 2005, pp. 550-558.

Schneider. T. A., Mikellides, I.G., Jongeward, G.A., Peterson, T., Kerslake, T.W., Snyder, D., and D. Ferguson, "Solar Arrays for Direct-Drive Electric Propulsion: Arcing at High Voltages," *J. of Spacecraft and Rockets*, Vol. 42, No. 3, May-June 2005, pp. 543-549.

Hoskins, W.A., Homiak, D., Cassady, R.J., Kerslake, T., Peterson, T., Ferguson, D., Snyder, D., Mikellides, I., Jongeward, G., Schneider, T., and M. Hovater, "Direct Drive Hall Thruster System Development, AIAA 2003-4726, 39th Joint Propulsion Conference, Huntsville, AL, July 20-23, 2003.

Dankanich, J.W., "Direct Drive for Low Power Hall Thrusters," AIAA 2005-4118, 41st Joint Propulsion Conference, Tucson, AZ, July 10-13, 2005.

Brandhorst, Jr., H.W., Best, S.R., Rodiek, J.A., O'Neill, M.J., and M.F. Piszczor, Jr., "Direct-Drive Performance of a T-100 HET Powered by Triple Junction, High-Voltage Concentrator PV Array, AIAA 2010-6620, 46th Joint Propulsion Conference, Nashville, TN, July 25-28, 2010.

Test Results of Direct-Drive of HET using a High-Voltage Multi-Junction-Cell Concentrator Array

IEPC-2009-052

Presented at the 31st International Electric Propulsion Conference, University of Michigan • Ann Arbor, Michigan • USA September 20 – 24, 2009

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Space Research Institute, Auburn University, AL, 36849, USA

Mark J. O'Neill[4]
Entech Solar, Inc., Ft. Worth, TX, 76177, USA

and

Michael F. Piszczor, Jr.[5]
NASA Glenn Research Center, Cleveland, OH, 44135

Abstract: Auburn University's Space Research Institute working with Entech Solar, Inc. has been conducting a "direct drive" experiment using a high-voltage (600 Voc), III-V multijunction Entech Solar SunLine concentrator array coupled to a Russian T-100 Hall Effect Thruster. This possibly is the first time III-V-based multi-junction solar cells have been used to run a Hall thruster powered directly at high voltage. This paper will discuss the set-up and testing results. Testing included the addition of Entech Solar's Stretched Lens Array hardware in a vacuum chamber to measure plume impingement effects at various positions relative to the exhaust axis of the thruster.

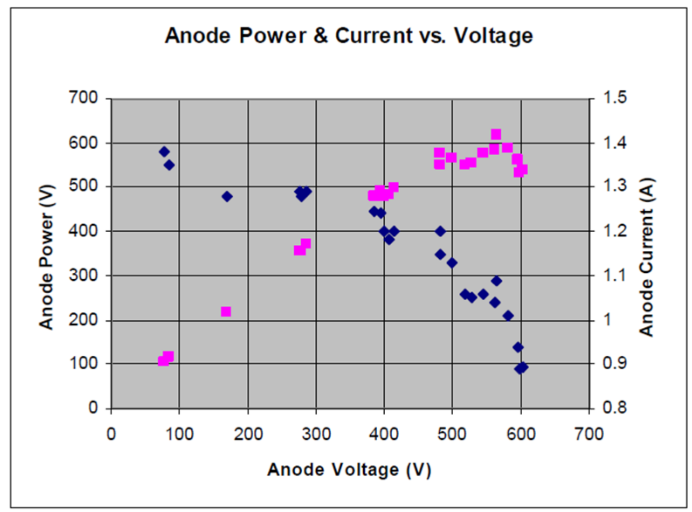


Figure 9. SunLine direct-drive of T-100 HET.

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology

“Experimental Investigation of a Direct-Drive Hall Thruster and Solar Array System at Power Levels up to 10 kW”

TUESDAY, JULY 31, 2012

EP-21. EP Mission Analysis and Concepts
Chair(s): Charles Garner (NASA-JPL) and John Snyder (Jet Propulsion Laboratory)
4:00 PM - 6:00 PM; Regency VI

5:00 PM - 5:30 PM	AIAA-2012-4068. Experimental Investigation of a Direct-Drive Hall Thruster and Solar Array System at Power Levels up to 10 kW *John S. Snyder; John R. Brophy; Richard R. Hofer; Dan M. Goebel; Ira Katz*

- **Talk by Steve Snyder tomorrow - Tuesday 5:00 PM**
- **“Hall thruster control and operation is shown to be simple and no different than for operation on conventional power supplies.”**

Fig. 1. The National Direct-Drive Testbed Solar Array.

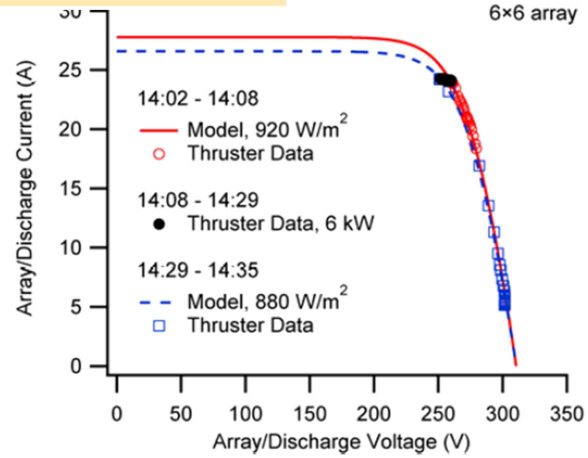


Fig. 4. Current-Voltage Curve for Selected Data of Fig. 3.

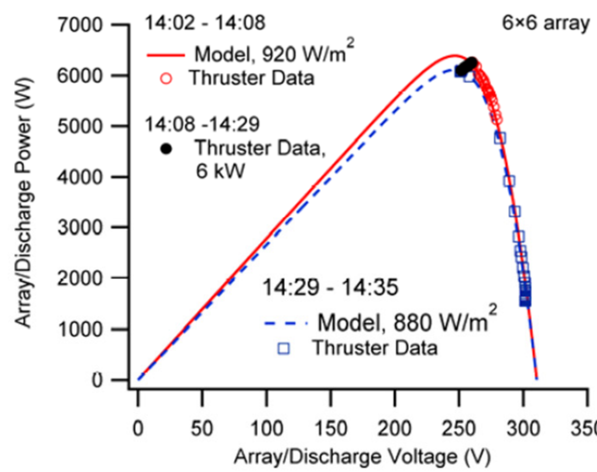
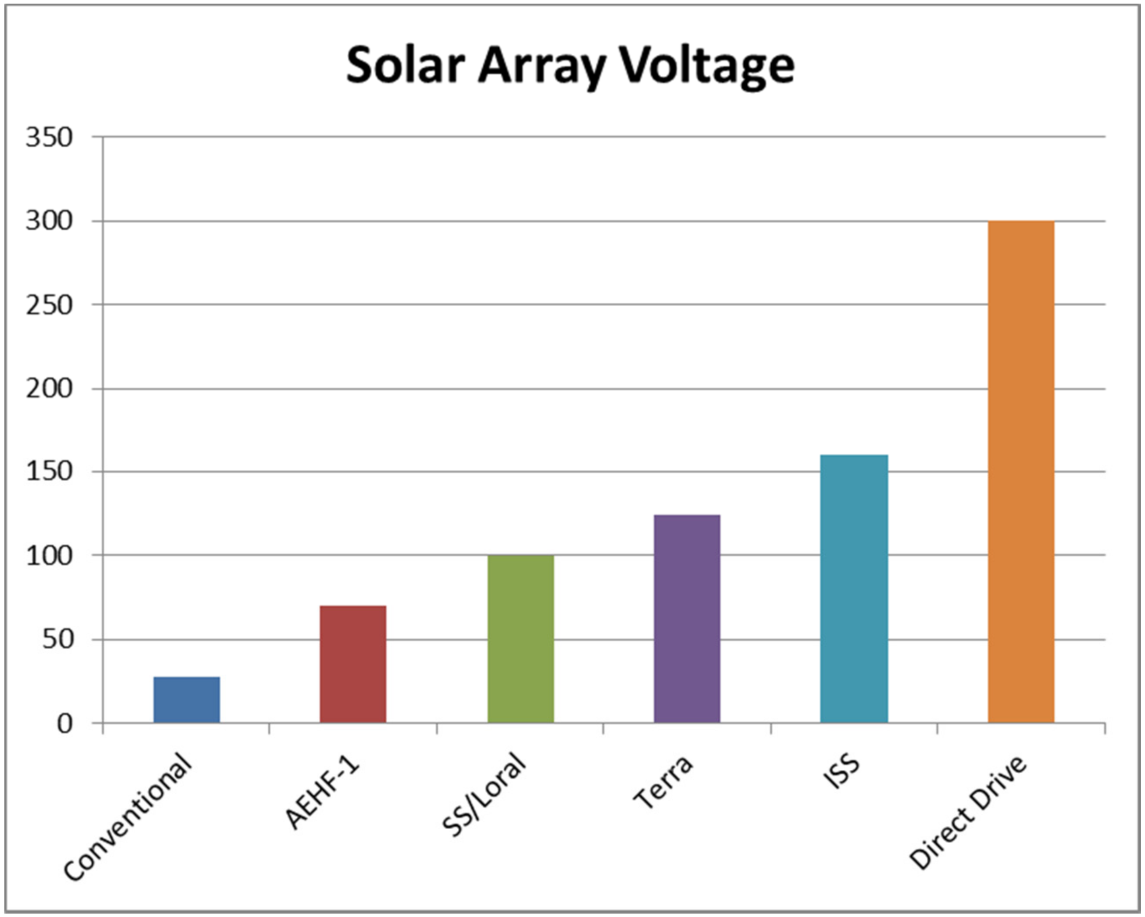


Fig. 5. Power-Voltage Curve for Selected Data of Fig. 3.

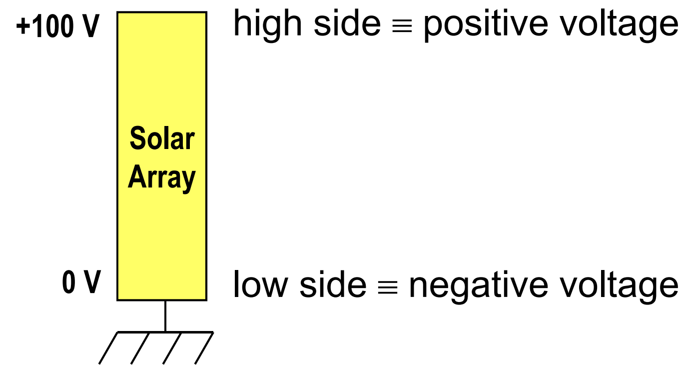
High Voltage Solar Arrays Needed for Direct Drive

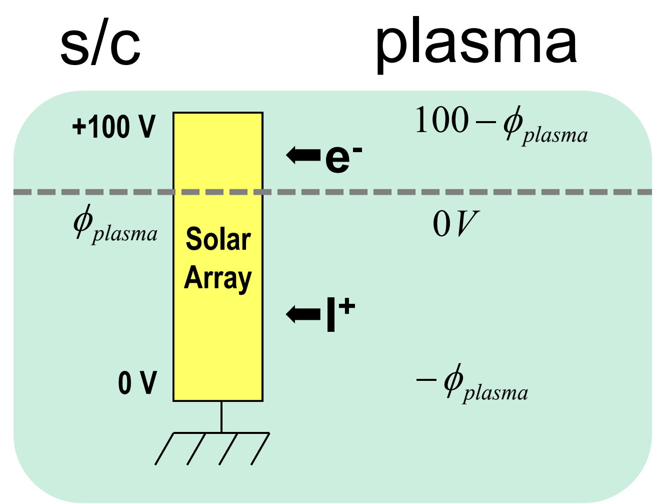
- Previous in-flight array experience below 170V, most below 100V



Solar Arrays Float Negative in a Plasma

- Solar array cells generate voltage wrt low side
  (low side often S/C ground)
- Current flows through the plasma
  positive conductors collect electrons
  negative conductors collect ions
- Electron current density >> ion current density
  Plasma quasi neutral
  $$n_e \approx n_i = n$$
  Ion & electron current densities
  $$j_e \approx n\,\mathrm{v}_e \qquad j_i \approx n\,\mathrm{v}_i$$
  Electron velocities >> Ion velocities
  $$\mathrm{v}_e >> \mathrm{v}_i \qquad |j_e| >> |j_i|$$
- Net current = 0
  $$I_e + I_i = 0 \qquad A^+ j_e + A^- j_i = 0$$
- $\boxed{\text{Negative area >> Positive area}}$
  $$A^- = A^+ \frac{|j_e|}{j_i} >> A^+$$





International Space Station Solar Arrays Collect Little Electron Current

AIAA-2002-0935

THE PLASMA ENVIRONMENT OF THE INTERNATIONAL SPACE STATION IN THE AUSTRAL SUMMER AURORAL ZONE INFERRED FROM PLASMA CONTACTOR DATA

Edgar A. Bering, III*, University of Houston, Houston, TX, Steven L. Koontz†, JSC / NASA, Houston, TX, Ira Katz‡, JPL / NASA, Pasadena, CA, Barbara Gardner§, SAIC, San Diego, CA, David S. Evans¶, SEL/ NOAA, Boulder, CO, and Dale C. Ferguson#, GRC/ NASA, Cleveland, OH

- ISS PCU is a hollow cathode connected to S/C ground (array low side)
- ISS 160V Arrays
  - ISS solar array wing consists of two retractable "blankets" of solar cells with a mast between them.
  - Wing 34 meters long x 12 meters wide
  - ISS had 2 wings (max ~65 kW) when the PCU data was taken
- Ionosphere plasma currents less than 1 mA per string

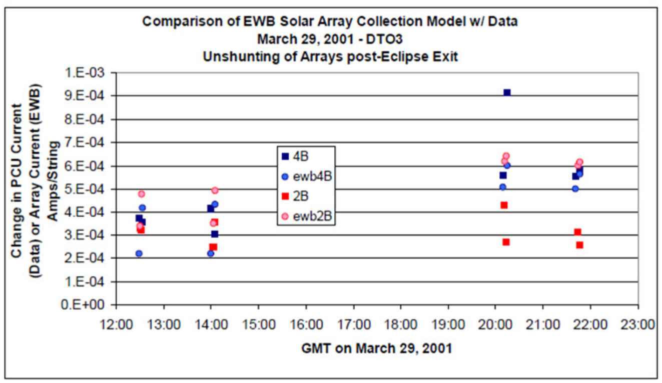


Figure 11. Comparison of string current calculated using EWB, and March 29 DTO data.

M.J. Mandell, V.A. Davis, B. Gardner, & G. Jongeward, "ELECTRON COLLECTION BY INTERNATIONAL SPACE STATION SOLAR ARRAYS", *8th Spacecraft Charging Technology Conference, NASA/Marshall Space Flight Center, Alabama, October, 2003*.

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Pioneering Work on HV Solar Array Plasma Interactions Done at NASA/GRC

INVESTIGATION OF HIGH VOLTAGE SPACECRAFT SYSTEM INTERACTIONS WITH PLASMA ENVIRONMENTS

N. John Stevens, Frank D. Berkopec, Carolyn K. Purvis,
Norman Grier, and John Staskus

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

AIAA/DGLR 13th INTERNATIONAL ELECTRIC PROPULSION CONFERENCE
San Diego, California April 25-27,1978

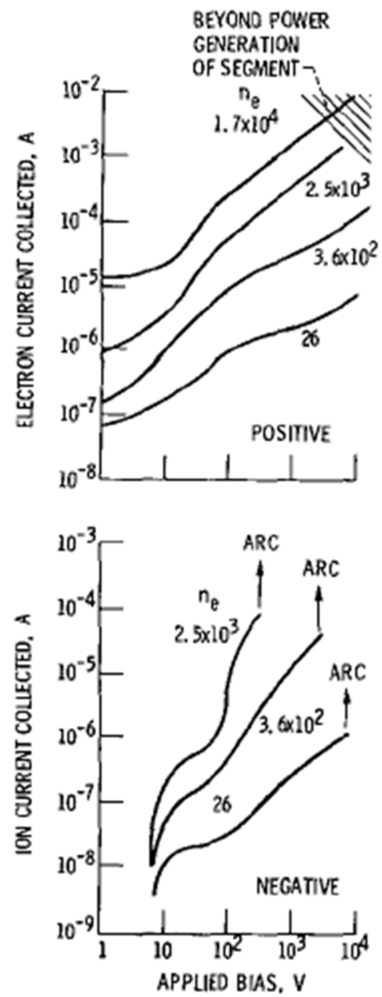


Figure 4. - Ground test results. Solar array segment; 1058 cm^2 area.

Positive potentials

No arcing

Parasitic current losses is the issue

Negative potentials

Solar array arcing is the issue is

Steep Gradients Cause Negative Potential Arcing

Positive Potentials | **Negative Potentials**

“snap over”

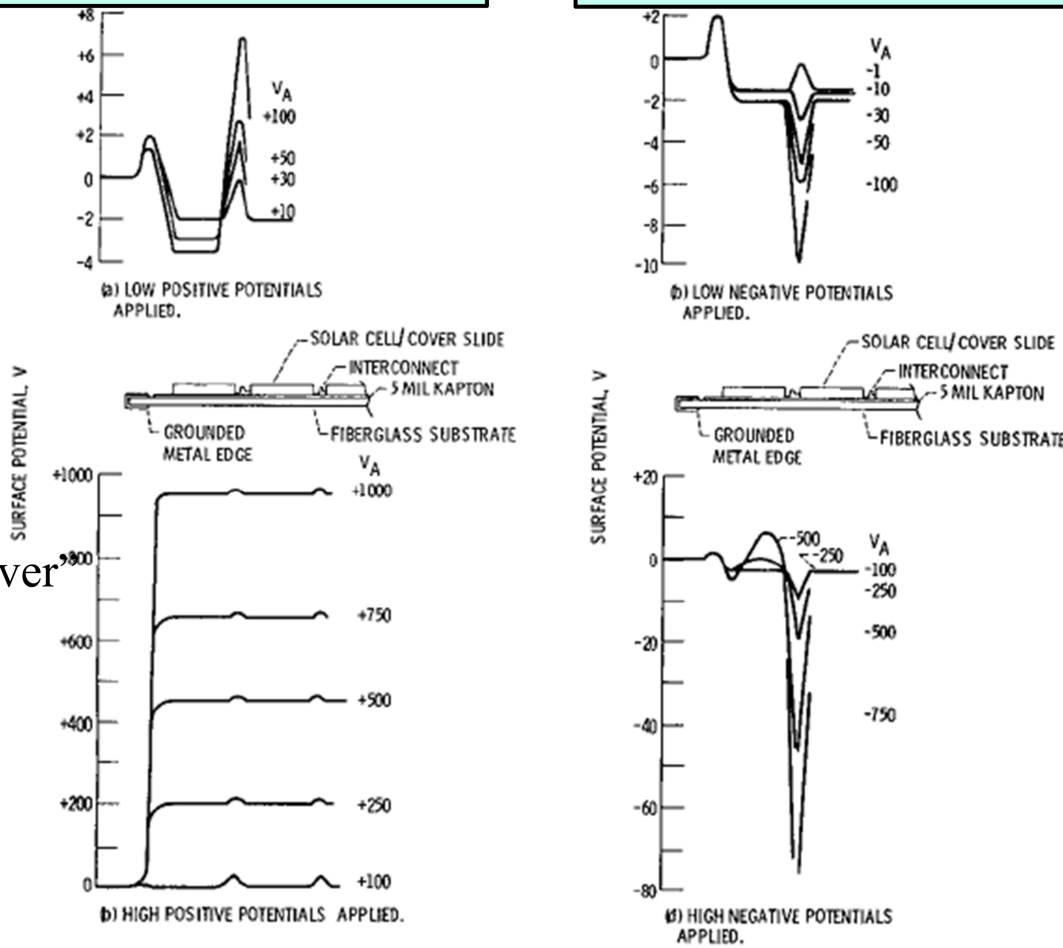


Figure 14. - Typical surface voltage profiles solar array segment.

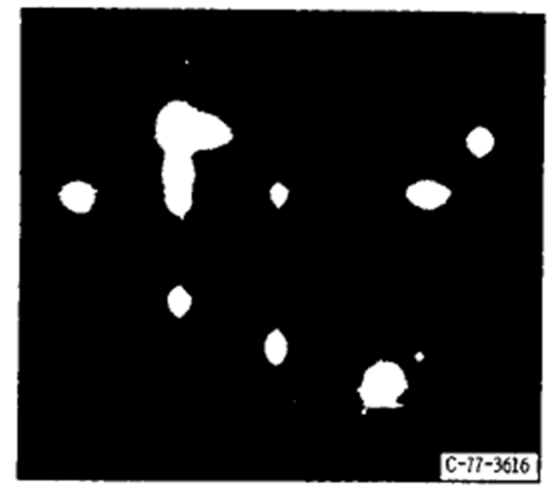


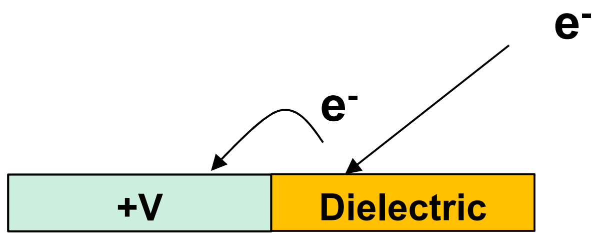
Figure 15. - Arcing on solar cells array sample (cell side) 2x4 cm wraparound cells on Kapton.

Both ions and electrons generate secondary electrons

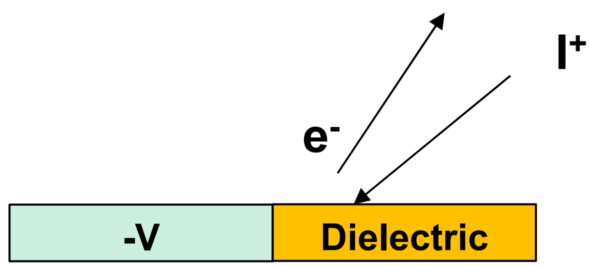
- Electron generated secondary electrons smooth potential gradients
- Ion generated secondary electrons steepen potential gradients

Metal-Dielectric-Plasma Triple Point

- Positive potential on metal
  - Electrons strike dielectric and generate secondary electrons
  - Result: enhanced collection & reduced edge fields



- Negative potential on metal
  - Ions strike dielectric and generate secondary electrons
  - Result: enhanced edge fields & arcing



Theory: Mandell, M. J., and Katz, I., "Potentials in a Plasma Over a Biased Pinhole," *IEEE Transactions on Nuclear Science*, Vol. NS-30(6), p. 4307, 1983.

Disk on Kapton

Positive Potentials | **Negative Potentials**

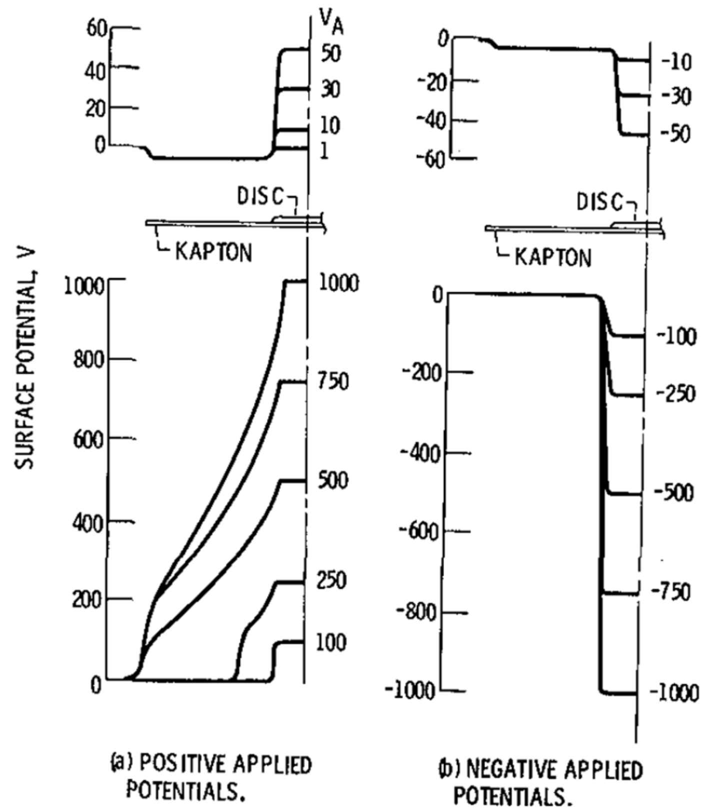


Figure 11. - Typical surface voltage profiles. Disc on Kapton.

Data: N.J. Stevens, et al., AIAA 78-672

Plasma Collection for "Solar Power Satellites" with Kilovolt Solar Arrays

VOL. 18, NO. 1, JAN.-FEB. 1981 J. SPACECRAFT 79

AIAA 80-0042R

Plasma Collection by High-Voltage Spacecraft at Low Earth Orbit

I. Katz,* M. J. Mandell,† G. W. Schnuelle,†
D. E. Parks,‡ and P. G. Steen§
Systems, Science and Software, La Jolla, Calif.

A computer model of the three-dimensional sheath formation and plasma current collection by high-voltage spacecraft has been developed. By using new space charge density and plasma collection algorithms, it is practical to perform calculations for large, complex spacecraft. The model uses objects and geometries compatible with the NASA Charging Analyzer Program (NASCAP). Results indicate that ion focusing observed in the laboratory during high-voltage collection experiments is probably due to voltage gradients on the collecting surfaces.

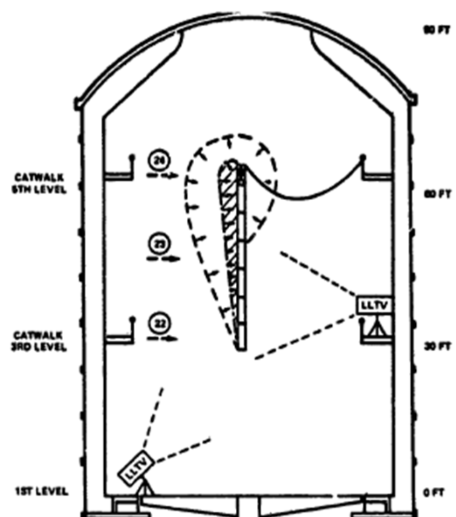


Fig. 3 - High Voltage "array" test lay-out in Chamber A

[4]McCoy, J.E. and Konradi, A., "Sheath Effects Observed on a 10 Meter High Voltage Panel in Simulated Low Earth Orbit Plasma," *Spacecraft Charging Technology-1978*, NASA Conference Publication 2071, AFGL-TR-79-0082, 1979, p. 315.

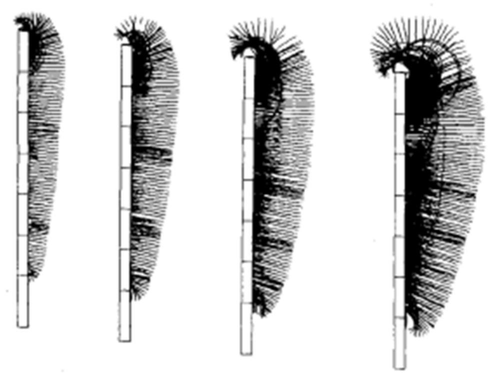


Fig. 4 *y-z* **views of electron sheath particle trajectories for cases 4-7 (left to right).**

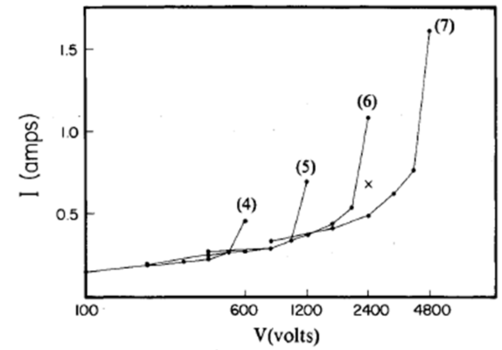


Fig. 6 Current per 1.44-m^2 section of panel vs potential for cases 4-7 (left to right).

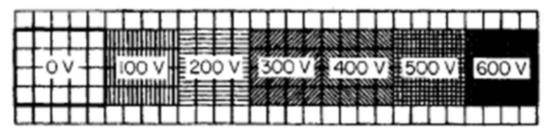


Fig. 1 Test object for sample calculations.

VOL. 19, NO. 2, MARCH-APRIL 1982 J. SPACECRAFT 129

AIAA 81-0740R

Parasitic Current Losses Due to Solar-Electric Propulsion Generated Plasmas

I. Katz,* D.E. Parks,† M.J. Mandell,‡ and G.W. Schnuelle‡
Systems, Science and Software, La Jolla, Calif.

Solar-electric propulsion is a leading candidate for many upcoming space missions. Under many circumstances plasma produced by charge-exchange reactions within the ion beam dominates the ambient environment near the spacecraft. The calculations presented here contain a predictive hydrodynamic model for the charge-exchange plasma expansion and a fully three-dimensional model for the structure of the plasma sheath around the solar array wing. Results of calculations for several configurations and voltage levels indicate that with kilovolt biases power losses of ~10% or more are likely, even with only one engine in operation, and that ameliorative measures should focus on the inboard portion of the solar arrays.

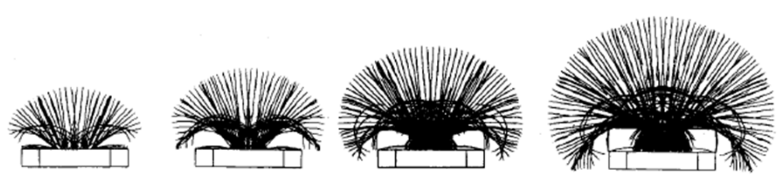


Fig. 5 *x-y* **views of electron sheath particle trajectories for cases 4-7 (left to right).**

Arcs that Can Damage High Voltage Solar Arrays

36th AIAA Aerospace Sciences Meeting and Exhibit, 1998 AIAA 1998-1002

Mechanism for Spacecraft Charging Initiated Destruction of Solar Arrays in GEO

Ira Katz*
V. A. Davis*
Maxwell Technologies Inc., San Diego, CA 92123

David B. Snyder**
NASA Lewis Research Center, Cleveland, OH 44140

Recently, there have been anomalies on geosynchronous communications satellites that have lead to failures of strings on the solar arrays. The symptoms of the failures are low impedance shorts between high and low voltage cells on a string, and shorts between high voltage cells and the array ground. All of the anomalies occurred when other, instrumented, satellites measured a charging environment. In this paper we present a theory and supporting laboratory data, which show how small, low energy, spacecraft charging arcs on solar arrays can lead to larger, sustained discharges, which permanently damage the solar arrays. While observed in GEO, this mechanism can also lead to array destruction in LEO.

EOS-AM Solar Array Arc Mitigation Design

Stuart Davis and Robert Stillwell
TRW Space and Defense

William Andiario
Lockheed Martin Missiles and Space

David Snyder
Glenn Research Center

Ira Katz
Maxwell Technologies

ABSTRACT

This paper discusses the design and test program initiated to retrofit the EOS-AM solar array, protecting it from a newly discovered damage mechanism that is initiated by electrostatic discharges (ESD) while in orbit.

INTRODUCTION

Solar array power loss on two commercial geosynchronous satellites has been attributed to an ESD initiated damage mechanism that is applicable to high voltage solar arrays.[1,2] Solar arrays are known to arc on orbit. These electrostatic discharges do not contain enough energy to cause damage. When they occur

susceptible to the same damage mechanism. Arc mitigation implemented to protect the solar array consists of isolation diodes, limited insulative "grouting" and insulating covers and tapes. The mitigation design was validated through further testing at GRC. The ESD mitigation design is discussed in detail in this paper.

OVERVIEW OF ARC DAMAGE MECHANISM

In LEO, the spacecraft charging environment consists of a low temperature (a fraction of an electron volt) plasma with densities ranging from 10^5 to 10^6 particles per cm^3. The floating potential of a spacecraft in this environment is affected by the bus voltage and the area of the solar

Solar Array Augmented Electrostatic Discharge in GEO

Christopher F. Hoeber*
Ernest A. Robertson**
Space Systems/Loral, Palo Alto, CA 94303

Ira Katz**
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David B. Snyder**

NASA Lewis Research Center, Cleveland, OH 44140

Abstract

During 1997, Space Systems/Loral (SS/L) launched five high-powered spacecraft which generate over 10 kW of electrical power at beginning of life (BOL). On two of those spacecraft there has been damage to the solar arrays during the first year of operation. Extensive analysis and ground testing has demonstrated that a damage mechanism exists in which electrostatic discharges occurring between the coverglass slides and the solar cells on the solar arrays can be sustained by current from the solar array itself. Depending on the physical construction of the array, local heating can cause pyrolization of the insulation which separates the solar cells from the conductive substrate, thus resulting in short circuits of individual strings. Susceptibility to this phenomenon is likely to increase throughout the industry as spacecraft power increases lead to larger solar arrays operating at higher voltages. However, analytical modeling and laboratory experimentation have verified the phenomenon and validated the preventative actions undertaken by SS/L so that this phenomenon can be controlled on future spacecraft.

1. The Spacecraft Anomalies

The anomalies observed on the SS/L spacecraft are consistent with failures of strings of cells on the solar arrays. The symptoms of the failures are low impedance shorts between cells at different points within a string, and shorts between high voltage cells and the array ground, as illustrated in **Figure 1**. All of the anomalies occurred when other, instrumented, satellites measured a charging environment characteristic of a solar substorm.

In a previous paper[1] a theory and supporting laboratory data were presented, showing how small, low energy, spacecraft charging arcs on solar arrays can lead to larger, sustained discharges, in turn leading to permanent damage of the solar arrays. Since the publication of reference 1, additional work has led to a solid understanding of the phenomenon, of the existence of a cell-to-cell voltage threshold below which the sustain-

* Associate Fellow AIAA
** Member AIAA

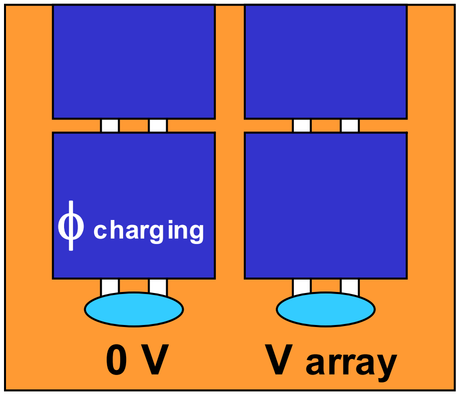
page 1

AIAA 1998-1401

National Aeronautics and Space Administration

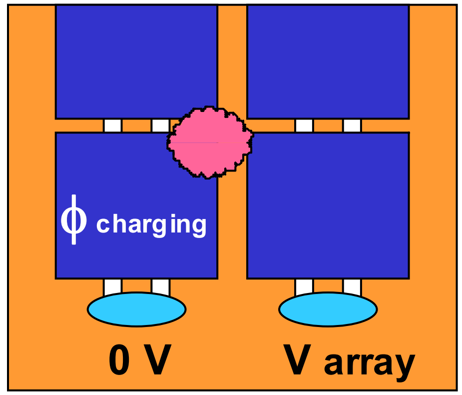
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Discharge Scenario



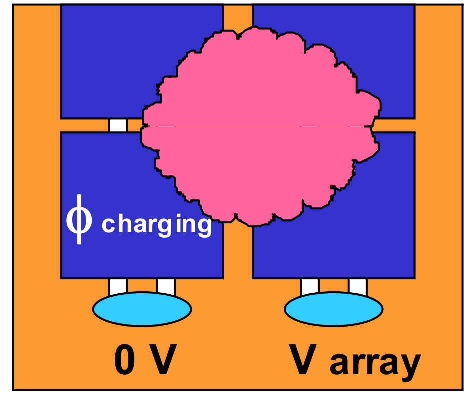
Solar Cells charge in response to space environment

Solar Cell - Coverslip E field > 4 x 10^5 V/m



Spacecraft Charging Causes a small arc to occur in the gap between cells.

Small Discharge Starts in Gap Between Cells Discharge Generates a Plasma Cloud



The spacecraft charging arc triggers a sustained discharge driven by the array string current and voltage

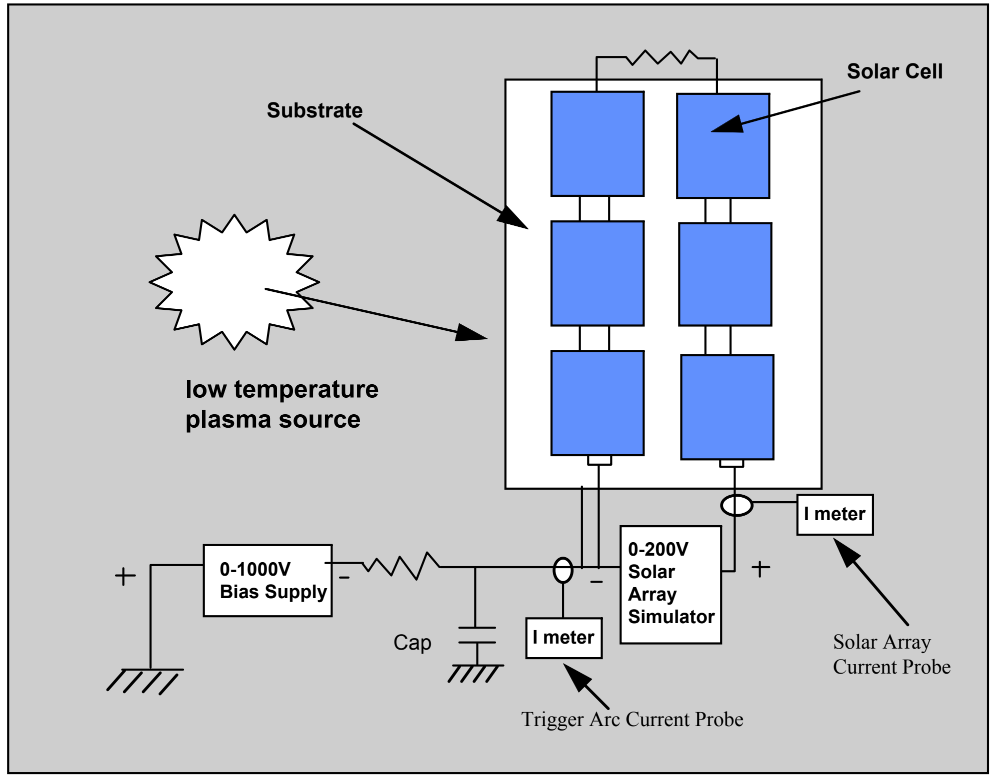
Plasma Cloud Provides Low Impedance Path Across String

1. Spacecraft charging provides trigger arc (~300V)
2. Solar array string provides the power for surface flashover
3. Sustained surface flashover pyrolizes the kapton
4. Permanent low impedance path across string

I. Katz, V.A. Davis and D.B. Snyder, Mechanism for spacecraft charging initiated destruction of solar arrays in GEO, *AIAA Paper 98-1002, 35th Aerospace Sciences Meeting & Exhibit, January 12-15, 1998, Reno, NV.*

Design of Tests Conducted at NASA/LeRC

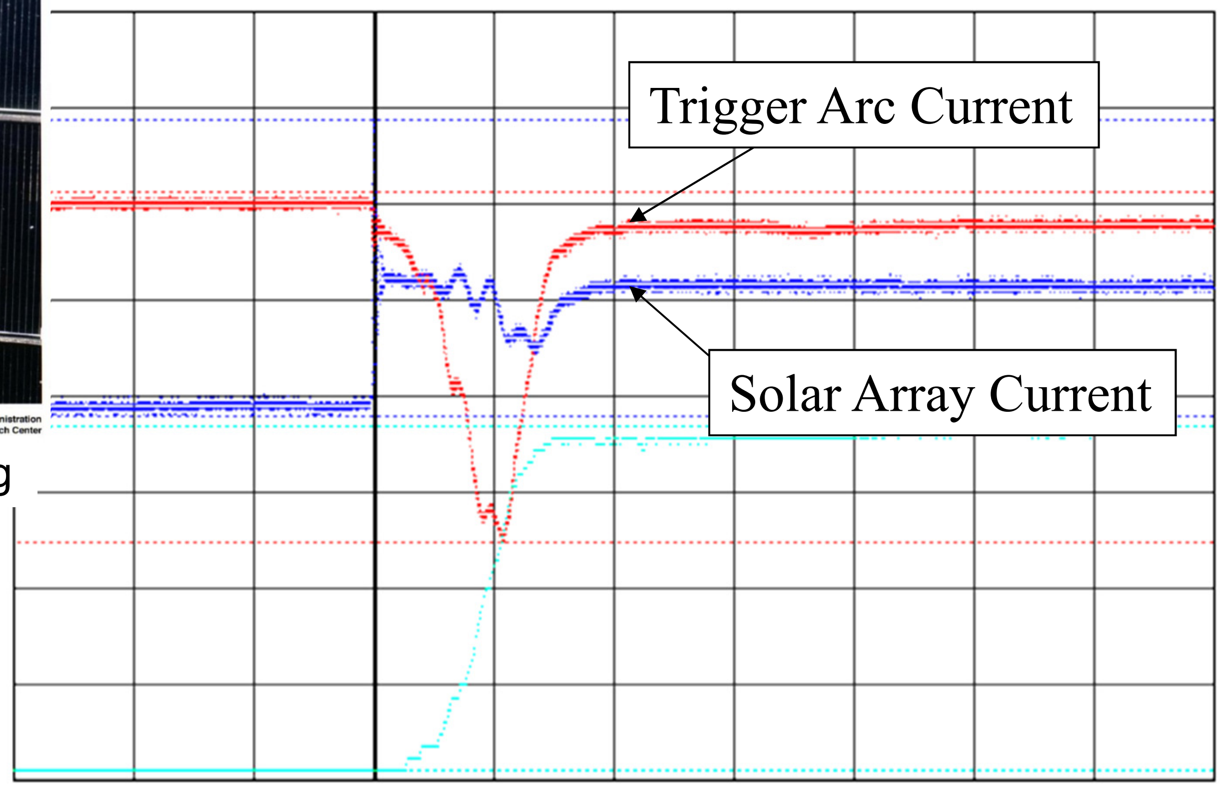
- Chamber Environment
  - Low density, ionosphere like plasma density ~ 10^{11} m^{-3}
  - Pressure < 10^{-6} Torr
- Solar Array Supply (SAS)
  - Purpose: Simulate the current generation capabilities of a string
- Charging Bias Supply (CBS)
  - Purpose: Simulate the sunlight charging of the array
  - Parameters: 0 – 1000V
    - capacitor to simulate wing capacitance
    - positive terminal attached to tank ground
    - 10KΩ current limiting resistor
- Diagnostics
  - Current on the SAS supply
  - Current on the CBS supply
  - Low level TV with time stamp
  - Transient pulse monitor
- Test Procedure
  - Step from –200V to –1000V in 50V steps
  - Dwell the order of an hour at each step to allow differential to develop



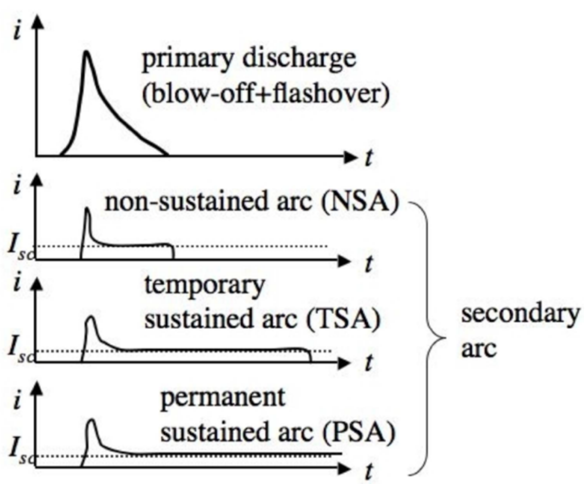
C.F. Hoeber, E.A. Robertson, I. Katz, V.A. Davis and D.B. Snyder : Solar array augmented electrostatic discharge in GEO, *AIAA Paper 98-1401, 17th International Communications Satellite Systems Conference and Exhibit, Yokohama, Japan, Feb. 23-27, 1998*

Example Test Data - Array Sustained Discharge

Photo from EOS-AM1 testing



Terminology



Failure Thresholds

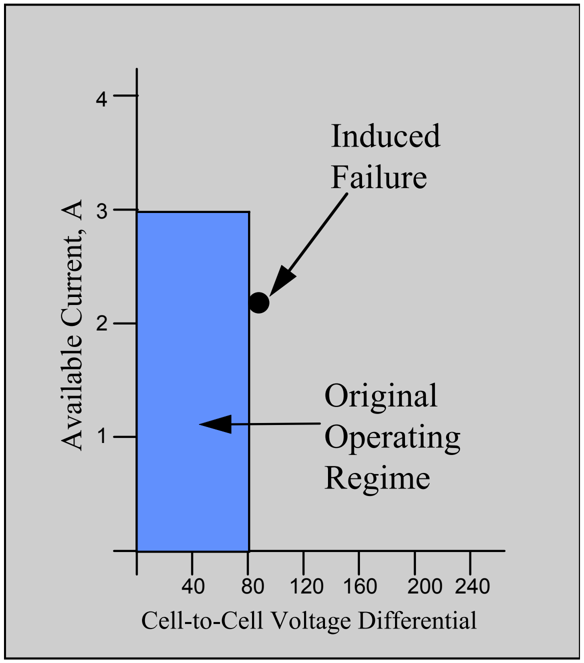


Figure 14. *Measured GaAs Coupon Failure Threshold*

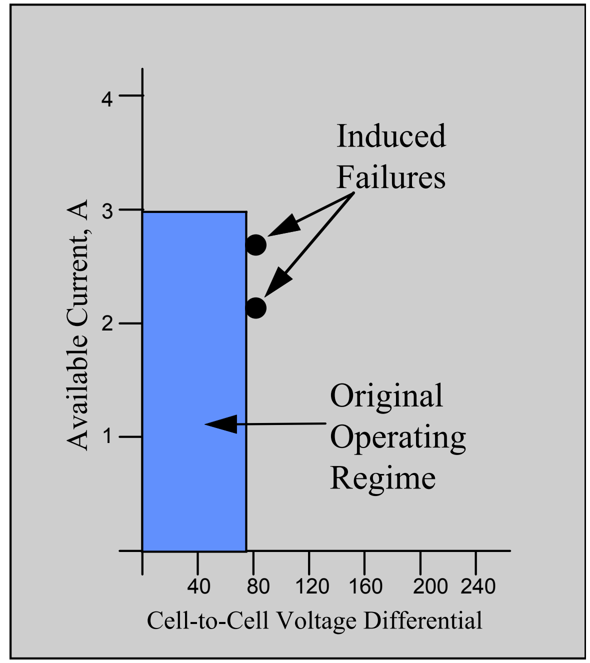


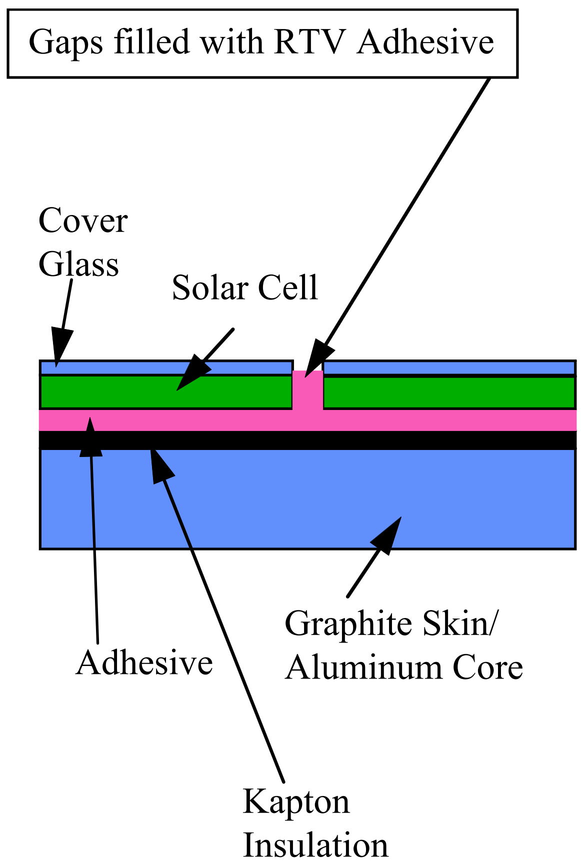
Figure 15. *Measured Si Coupon Failure Threshold*

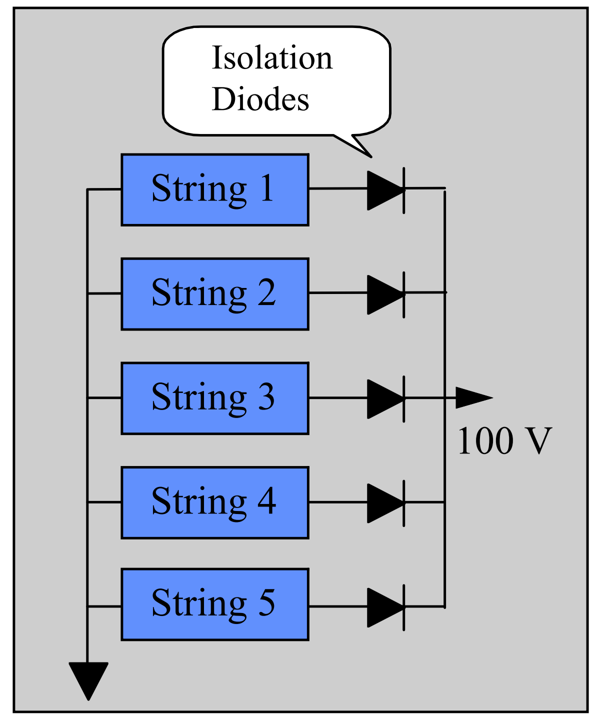
C.F. Hoeber, E.A. Robertson, I. Katz, V.A. Davis and D.B. Snyder : Solar array augmented electrostatic discharge in GEO, *AIAA Paper 98-1401, 17th International Communications Satellite Systems Conference and Exhibit, Yokohama, Japan, Feb. 23-27, 1998*

SS/L Corrective Actions

1. All solar array panels were rewired so that the voltage between adjacent cells is 50 V or less
2. An RTV barrier, was inserted in all gaps between cells of differing voltages, and for a width of at least 10 mm in the crossing gaps between series cells
3. Each string is isolated by diodes, limiting the current available to an arc

C.F. Hoeber, E.A. Robertson, I. Katz, V.A. Davis and D.B. Snyder : Solar array augmented electrostatic discharge in GEO, *AIAA Paper 98-1401, 17th International Communications Satellite Systems Conference and Exhibit, Yokohama, Japan, Feb. 23-27, 1998*





Effectiveness of the RTV Barrier

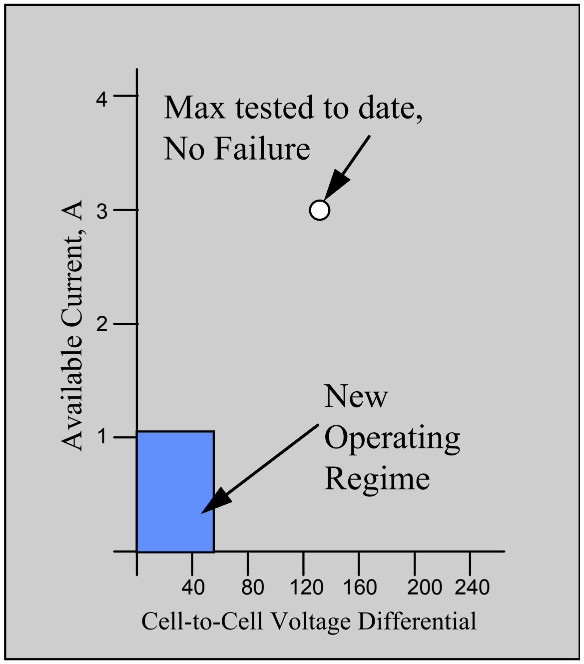


Figure 16. *GaAs Coupon Failure Threshold with RTV Barrier Installed*

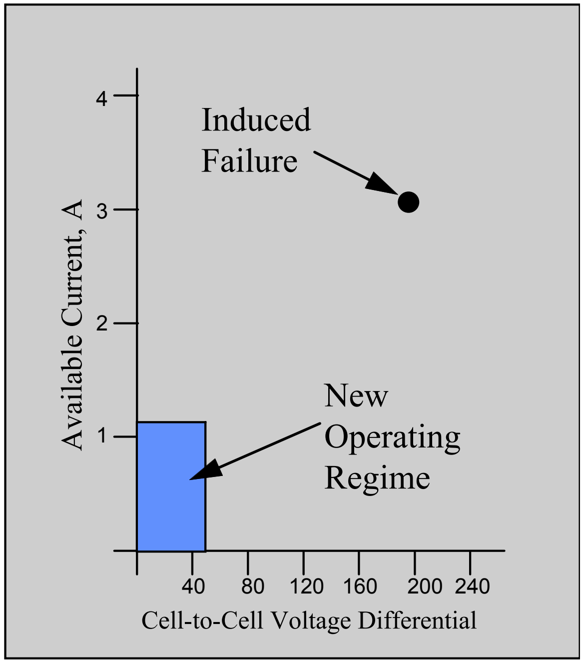


Figure 16*. Si Coupon Failure Threshold with RTV Barrier Installed*

C.F. Hoeber, E.A. Robertson, I. Katz, V.A. Davis and D.B. Snyder : Solar array augmented electrostatic discharge in GEO, *AIAA Paper 98-1401, 17th International Communications Satellite Systems Conference and Exhibit, Yokohama, Japan, Feb. 23-27, 1998*

Testing Embodied in ISO Standard

Introduction to ISO-11221, Space Systems – Space Solar Panels – Spacecraft Charging Induced Electrostatic Discharge Test Methods

La SEINE

Mengu Cho
Laboratory of Spacecraft Environment Interaction Engineering
Kyushu Institute of Technology
Kitakyushu, Japan

September 22, 2010
11th Spacecraft Charging Technology Conference, Albuquerque, NM, USA 1

Test facility

- If it can be confirmed that the probability of a transition from a primary discharge to a secondary arc does not depend upon the method of primary discharge inception, *any method can be used to cause primary discharges, irrespective of the anticipated charging situation in orbit.*
- The test shall take place under vacuum in a test chamber with a pressure that guarantees the physical state of a collisionless plasma if a low energy plasma is used, or lower than 3×10^{-3}Pa if other triggering methods such as an energetic electron beam, UV ray, laser pulse, etc., are used.

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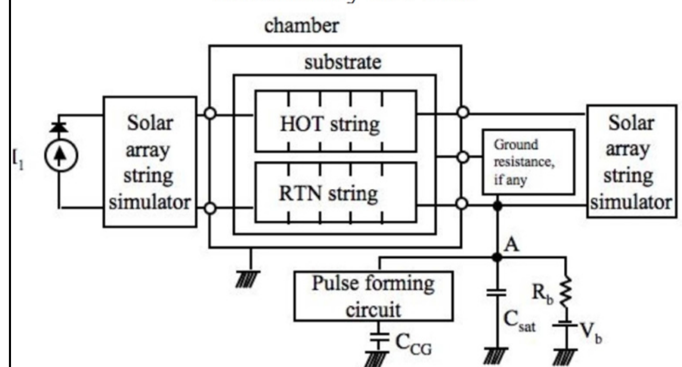
Introduction

- Papers on GEO satellite accidents
  - Katz and Snyder, AIAA 1998-1002, 1998
  - Hoeber, Katz and Snyder, AIAA 1998-1401, 1998
- 7th SCTC (ESA-ESTEC, 2001)
  - Difference of test methods
  - Values of external capacitance
  - How to test, plasma or beam?
- 8th SCTC (Huntsville, 2003)
  - Round-robin discussion on standardization

5

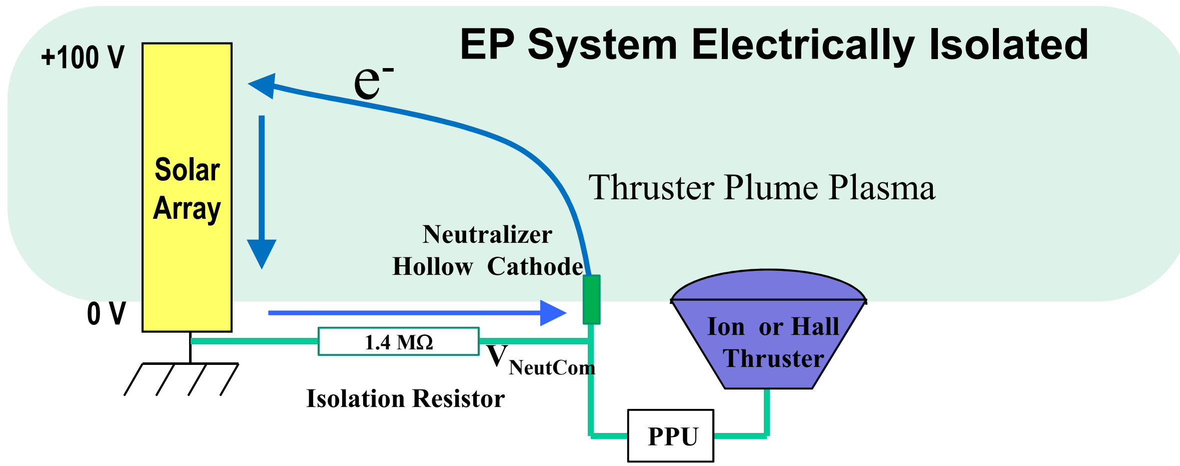
Secondary arc test

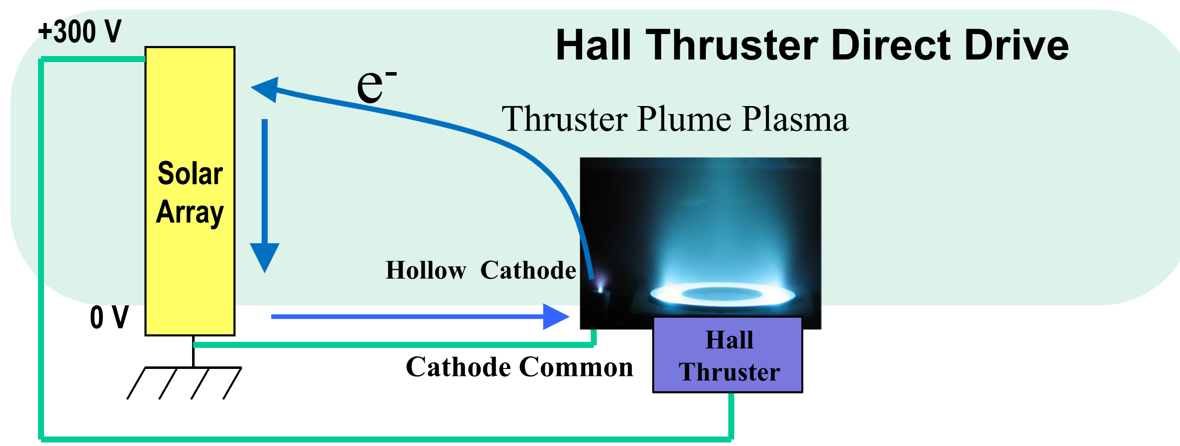


Current Flow in EP Thruster Plasma Plumes

- Electrons and ions from the thruster plume plasma and can be collected by exposed potentials on the solar array

- Two grounding schemes
  1. EP System Electrically Isolated from Spacecraft Ground through a resistor
     - e.g. NASA's Dawn Spacecraft
     - Current through the plasma changes "Neutralizer Cathode Common" voltage
  2. Direct Drive
     - "Cathode Common" tied to the low side of the array
     - Hall thruster anode tied to array high side
     - "Parasitic" currents flow through the plume
     - Reduced arcing!





National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Plasma Currents on the Dawn Spacecraft

44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference
20-23 July, 2008, Hartford, CT
AIAA-2008-4917

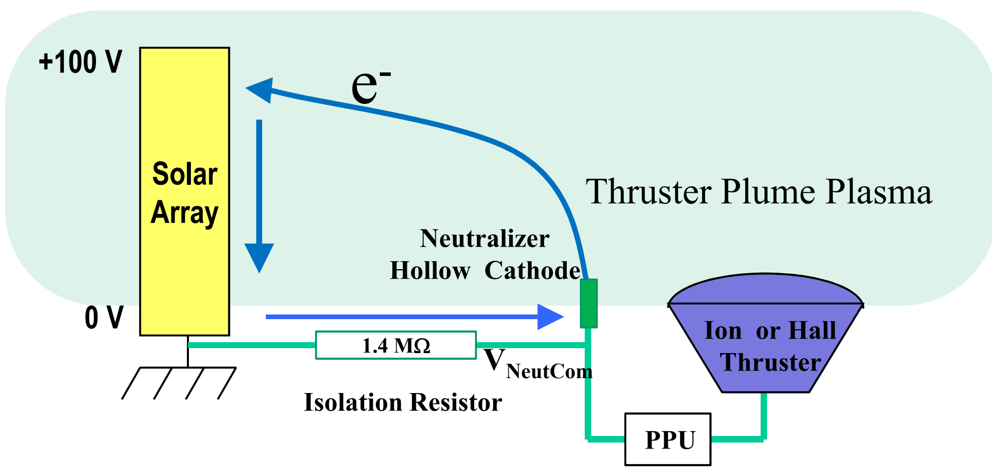
Dawn Ion Propulsion System – Initial Checkout after Launch

John R. Brophy[1], Charles E. Garner[2], and Steven Mikes[3]
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Neutralizer Common Voltage

During an attempt to run ion thruster FT2 at ML111 for a characterization test on DOY 2008-099, an unexpected shutdown occurred during the diode-mode preheat of the thruster. Telemetry indicated a Neutralizer Common Error was detected by the DCIU flight software (FSW) causing the DCIU to terminate diode-mode operation. A Neutralizer Common Error occurs when the neutralizer common voltage – the voltage between spacecraft ground and the neutralizer cathode – exceeds a preset limit of +40 V.

As described by Goebel and Katz [15], large positive values of the neutralizer common voltage can be caused by an interaction of the plasma created by the thruster and the high-voltage solar array. During thruster operation either in diode-mode or normal thrusting, this plasma interacts with the high-voltage solar arrays to drive the spacecraft ground potential negative of the ambient space plasma potential. The plasma created by the thruster is denser in diode-mode because of the lower ion velocities aggravating this effect. This denser plasma can result in the spacecraft ground potential being driven several 10's of volts negative of the space plasma potential. The thruster's neutralizer, however, clamps neutralizer common to within 15V of the space plasma potential. In the Dawn PPUs the impedance between neutralizer common and the spacecraft ground is 1.4 megaohms which is sufficiently large that a voltage difference of 10's of volts can be established between neutralizer common and the spacecraft ground.



- Neutralizer common floating potential ~40 V
- Resistor 1.4 MΩ

Current ~ 30 μA

- Solar Array Area 35 m^2

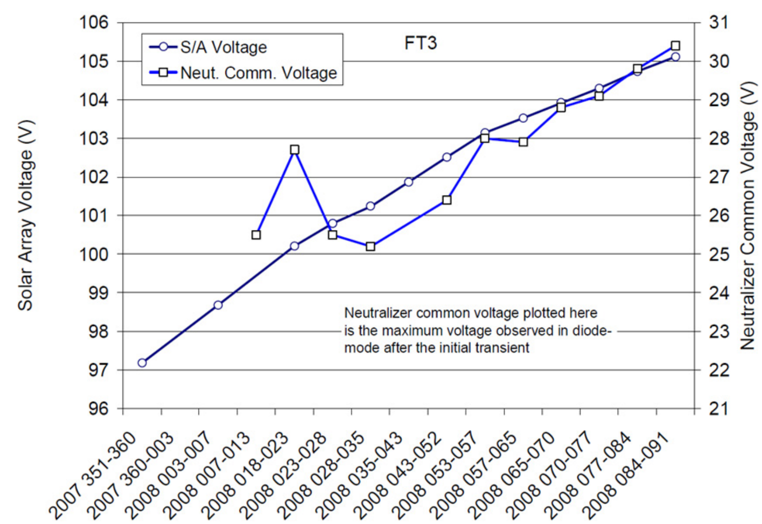
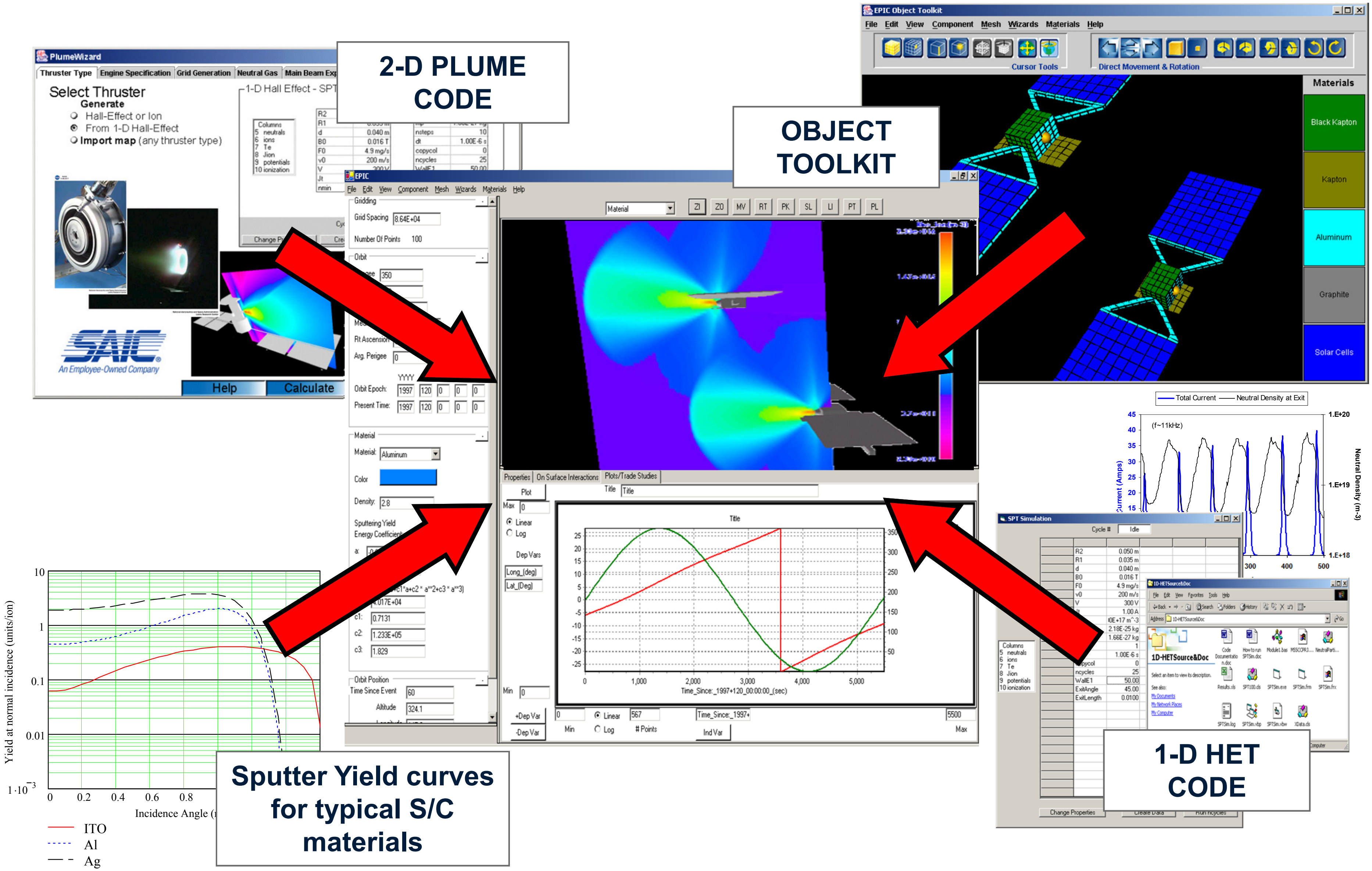


Fig. 23. Maximum observed neutralizer common voltage during diode-mode preheat increases with the solar array voltage.

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

EPIC: Integrated Computer Modules for the Assessment of Electric Propulsion –Spacecraft Interactions



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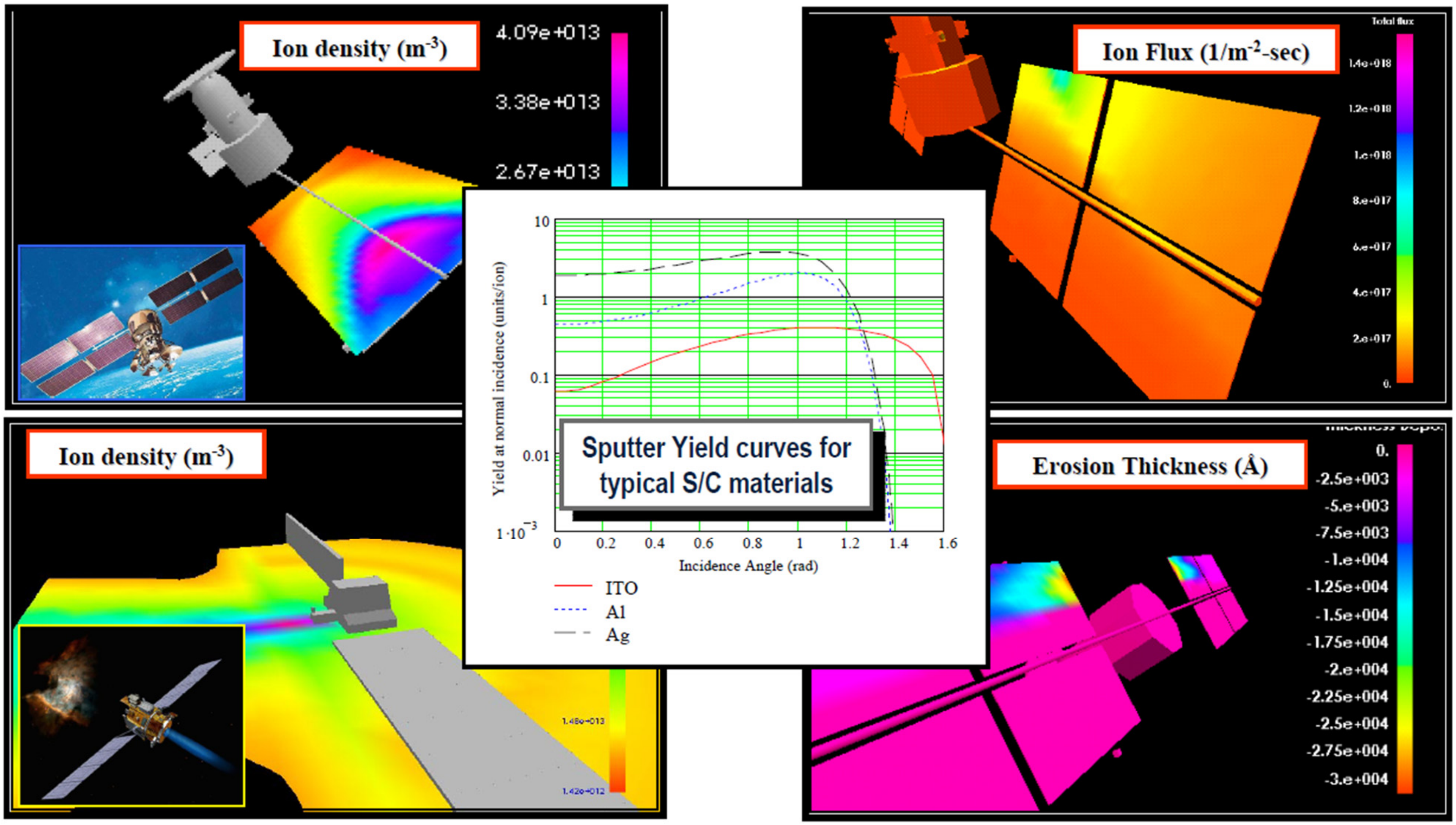
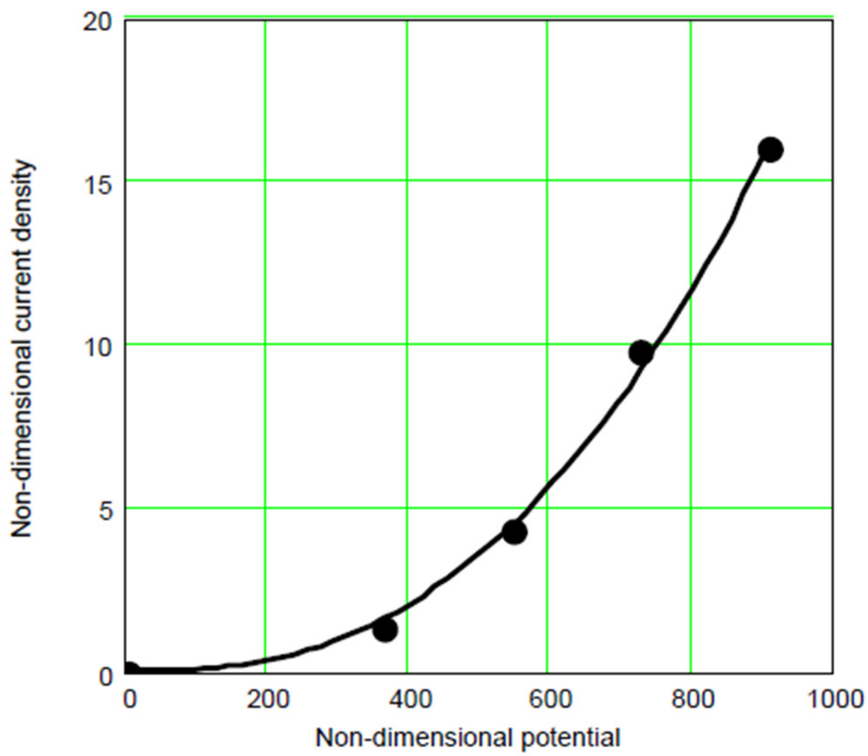
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

EPIC 3-D Interactions Tools

Material-specific interactions, time dependence, 3-D effects all within EPIC's capabilities.



Recent Studies of HV – Solar Array Interactions included Electron Collection and the Effects of On-Orbit Aging



Empirically-reduced dependence of non-dimensional electron collection $\bar{j}_{ec}$ as a function of nondimensional collection potential χ, based on averaged data from the TECSTAR coupon tests.

I.G. Mikellides, et al., "Solar Arrays for Direct-Drive Electric Propulsion: Electron Collection at High Voltages", *Journal of Spacecraft and Rockets*, Vol. 42, No. 3, May–June 2005

- Kenneth H. Wright, Todd A. Schneider, Jason A. Vaughn, Bao Hoang, Victor V. Funderburk, Frankie Wong, and George Gardiner, "Age Induced Effects on ESD Characteristics of Solar Array Coupons After Combined Space Environmental Exposures", 12^{th} Spacecraft Charging Technology Conference, May 2012
- Gaps in RTV ~ 250 μm x 25 μm

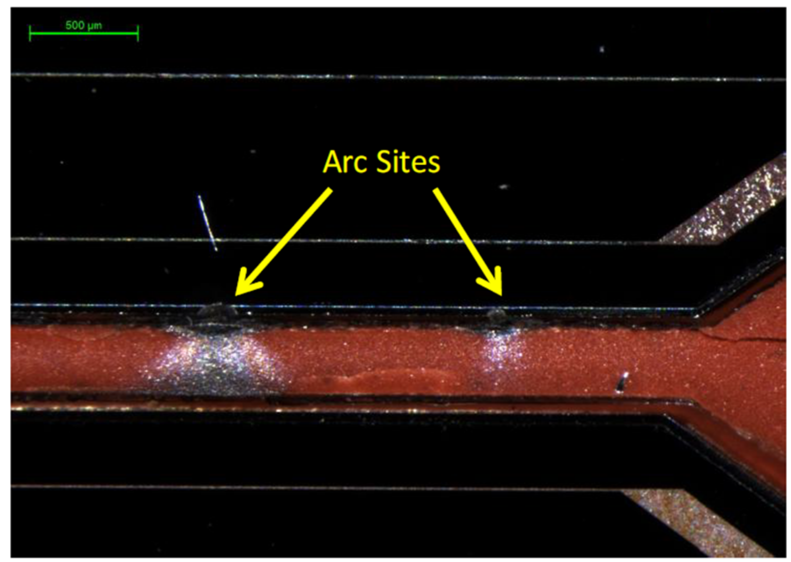


Fig. 6. Magnified image of a section of the area between strings on coupon A. The image reveals that the RTV contact with the cell edges is reduced and gaps have been created that allow for arc formation.

Parasitic Currents

- Solar cell
  e.g. Spectrolab XTJ
  Current density Jload min avg= 17.14 mA/cm² = 171 A/m^2
  Vload= 2.310 V
- String voltage
  Vstring= 300V
  Packing fraction fpack =0.8
  current density Jstring = 1 A/m^2

$$j_{string} = f_{pack} j_{cell} \frac{V_{cell}}{V_{load}} \approx 1 \ A/m^2$$

- Environment plasma Current densities

Environment	je	ne	Te
GEO	3E-06	1E+06	10,000
LEO	1E-02	1E+12	0.2
Hall (1m)	4	1E+14	2
Hall (3m)	0.4	1E+13	2
Hall (10m)	0.04	1E+12	2

- Current collected by a Gap in Grout 250 µm x 25 µm ~ 0.5 µA

SEP/HV Arrays and Spacecraft Interactions

- High Voltage Solar Array – Plasma Interactions have been studied for decades
  - Cells at <u>**negative potentials arc**</u>
  - Cells at <u>**positive potentials collect current**</u>
- Solar Arrays have successfully flown with voltages as high as 160 V
- Two approaches to Solar Electric Propulsion system designs
  - Conventional: Isolated electrically from solar array
  - Direct Drive: Cathode common connected to low side of the solar array
    - Advantages: Simpler & More efficient
    - Disadvantage: Requires higher voltage arrays
- Electric Propulsion Plasma Plumes interact with solar arrays
  - Currents collected by the arrays have been small
  - Higher voltage arrays will collect more current
  - Measures, such a grouting with RTV will limit current losses